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ABSTRACT

The modern history of biology shows how Darwin's selectionist theory has replaced instructionist theories in explaining the operations of living things: first with inheritance through the gene pool of the 1850s, and second with the replacement of a template theory of immune system function in the 1960s. Today scholars in several disciplines consider the brain a Darwin machine also. Underpinning Darwinism is a generative heuristic in which entities (or variants) are generated and later subjected to tests. Entities that survive the testing are re-generated. The premise of this paper is that the nature of both science and its learning can be understood through the application of this heuristic. The paper begins with an exposition of Darwin's conceptual synthesis and the recognition of its fundamental biological principles--generation of variants and selection from among those variants--in three specific domains. That recognition suggests the fruitfulness of these principles for understanding brain operation in general and generative learning in science in particular. The second section describes this biological view of learning and its three central characteristics. The last section initiates discussion of the worth of this biological basis for generative learning. Contains 57 references. (Author/PVD)

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A Neo-Darwinian View of Learning and Its Value for Science and Science Education

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A neo-Darwinian view of learning and its value for science and science education

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The modern history of biology shows how Darwin's selectionist theory has replaced instructionist theories in explaining the operations of living things: first, in the 1850's, with inheritance through the gene pool and second, in the 1960's, with the replacement of a template theory of immune system function. Now, scholars in several disciplines consider that the brain is a Darwin machine, too. Underpinning Darwinism is a generative heuristic, in which entities (or variants) are generated, and later subjected to tests. Entities which survive the testing are re-generated, and so on.
This heuristic offers considerable value for science education. In this paper, it will be argued that both the nature of science and of its learning can be understood through the application of this heuristic.

Introduction

We can perceive and wonder at the fit between most living species and the specific environments in which they live. Unlike most other species, homo sapiens can boast of adaptation to a large range of often quite inhospitable environments. As well, our species has developed a concern not only for its own survival, but also for the survival of the ecosystems of which we are a part. The knowledge which has allowed us to adapt to quite uncertain futures, and to try to hedge the survival chances of other species as well, resides largely in our science. Its history, though brief on an evolutionary time-scale, reveals it to be one of the richest, most highly developed and most successful (in terms of its achievements and predictions) of our culture's ways of knowing. The evolutionary process, through which we have developed brains and science, is both biological and cultural.

At the cutting edge of our own adaptation and the survival of our ecosystems, then, is science. As a consequence, so, too, are science education and science education research. Our contemporary society expects that learners will understand the contributions that science's great stories continue to make to the culture, that at least some learners will participate in developing elegant, contemporary and future scientific stories and that most learners will become discerning critics of new scientific directions.

However, by contrast with the theorising that has occurred in science, educational research has failed to yield a powerful and coherent explanatory "theory" of learning, spawning instead a variety of "approaches" (Thagard, 1992, p. 245). In fact, Ziman (1978/1991, p. 158) has gone so far as to ask, of the social sciences in general, if it is even possible to acquire "reliable, consensual knowledge about human behaviour." In 1957, in a treatise which is now recognisable as a watershed for educational research, Cronbach distinguished two categories of research approaches that could have been taken: experimental, in which "the experimenter is only interested in the variation which he himself creates" (p. 671), and correlational, in which "the correlator finds his interest in the already existing variation between individuals, social groups, and species" (p. 671). Cronbach's caution was clear: experimental research is well-suited to the investigation of ahistoric data, correlational research to the investigation of historic data. Despite Cronbach's warning, by 1993 Scarr was to state, with regret, that educational researchers had been "swayed by the experimental learning theories that dominated psychology in the mid-century ... [and had] traded Arnold Gesell for John Watson" (p. 1334).

Educational researchers' neglect of learners' evolutionary and life histories, in favour of a focus on the experimental "here-and-now," is a symptom of a much older, broader and more powerful ideology, one which had touched Darwin's ground-breaking synthesis over a century before. This idea, that humans are somehow special, is visible in the modern parting of the natural from the human sciences: much social science research considers human meaning-making (both shared within cultures and as individuals) to be discontinuous with the making of meaning in the rest of the living world. Such cultural studies, of which education was to form a part, devised purely social (rather than biological) explanatory frameworks for events, appealing to relationships between individuals' meanings and the (local and nonlocal) circumstances in which their actions took place (Erickson, 1986). It is our view, as it is Scarr's (1993) that such "cultural and social explanations complement but do not replace genetic/biological explanations" (p. 1334). As Gazzaniga (1992) pointed out,

> Modern humans have been playing in a very long ball game whose rules are complex and frequently appear at odds with our experience. Too much of academic psychology and modern brain science have been looking at and inspecting only a small aspect of the game - say second base. They take it apart, study it, theorize about it and all the rest, but fail to see that second base is part of a much larger biological and evolutionary context for considering the human mind. (pp. 6-7)

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In essence, what is being argued here is that education is, and ought to be considered to be, profoundly biological. As such, it can be well-explained in terms of fundamental biological principles, principles which in modern times have illuminated and, as will be seen here, united what appear, at first glance, to be diverse processes: inheritance, immune system function and the development of knowledge itself.

In this paper, we begin to develop that neglected biological basis for education with a consideration of learning itself, and we foreshadow our consideration of the teaching implications of such a view, to be undertaken in a later paper (Schaverien and Cosgrove, in preparation). The present paper is in three parts. It begins with an exposition of Darwin's conceptual synthesis and the subsequent recognition of its fundamental biological principles - generation of variants and selection from amongst those variants - in three specific domains. That recognition suggests the fruitfulness of these principles for understanding the operation of brains in general, and generative learning in science in particular. In the second part, we briefly describe this biological view of learning and then further illuminate it by focusing on its three central characteristics. In the final part, we initiate the detailed consideration which is now necessary if the worth of this biological basis for generative learning is to be explored.

1. Darwin's conceptual synthesis and the subsequent recognition of generation and selection in other domains

With the publication of *The Origin of Species*, Darwin proposed the following five largely independent theories (Mayr, 1982):

1. "That the world is not constant, but the product of a continuing process of evolution" (Mayr, 1982, p. 506).
2. "That all organisms have descended from common ancestors" (Mayr, 1982, p. 507).
3. That this descent takes place "by a continuous (gradual) process of branching" from those common ancestors (Mayr, 1982, p. 507).
4. "That populations are the *locus operandi* of speciation [permitting] every grade of intermediacy between geographical varieties and species" (Mayr, 1982, p. 508).
5. That evolution occurs by natural selection.

Despite its power, Darwin's (1859) evolutionary theory was not immediately accepted. Three reasons for its lack of immediate acceptance can be identified. First, Darwin's theories were impeded by strongly held opposing "prior" views: for example, although belief in creationism was not as strong as it had previously been, there was still a strong view that humans were special and not continuous with the rest of the living world. Despite Darwin's theories, this ideology survived and strengthened and is strongly visible, many years later, in the anthropological studies of Mead (cited and criticised by Freeman (1983) for taking humans out of nature). Secondly, at the time they were proposed, Darwin's theories lacked a corroborating mechanism: Darwin could not specify "the source of the variation that the theory demands, and he had no idea as to how selected variants are passed from parents to offspring" (Plotkin, 1994, p. 33). These problems were not to be resolved until 1900 when a paper by Mendel, describing factors or genes and published in 1866, was rediscovered (cited in Mayr, 1982). Thirdly, Darwin's theories proposed different and more subtle explanations to account for observed phenomena from those that were accepted at the time. For example, Darwin's theory of speciation undermined the idea that species were manifestations of essences. Also, he explained apparent discontinuities between species in terms of a combination of variation and extinction, which caused gaps in the evolutionary account, thereby justifying his belief in gradualism (Mayr, 1982).

However, in the years since they were first proposed, the power of selectionist accounts in several seemingly diverse domains has gradually begun to be recognised. Three such domains are relevant here:

1. In what has been termed the neo-Darwinian synthesis (Dawkins, 1986), inheritance has been explained by means of the generation of a population in which there is significant genetic variation and from which variants are later selected when and if particular organisms survive to reproductive maturity.

2. The triggering of antibody production in the immune system, long thought to have been an instructive process (in which an antigen acted as a template for the production of antibodies) was instead found to occur by means of selection from a large pool of already-existing antibodies (see, for example, Changeux, 1985 and Edelman, 1992).

3. The generation of scientific knowledge itself is now well-explained in terms of selection. Campbell (1960) proposed a theory of blind variation and selective retention in creative thinking (in science and in other pursuits) and Popper (1968) argued that science progresses by means of the survival of those theories that are the fittest. In the hypothetico-deductive method which, for Medawar (1967/1982), characterised a scientist's thinking, imaginative and critical acts were identifiable, "[alternating] so rapidly, at least in the earlier stages of constructing a theory, that they are not spelled

out in thought " (p. 134). More recently, Basalla (1988) and Vincenti (1990) have maintained that technological knowledge evolves by neo-Darwinian processes.

Just as, in 1859, the scientific world was saturated with evolutionary ideas before Darwin actually made them explicit (Miller and van Loon, 1982), so, we argue, the contemporary world is ripe for a fully neo-Darwinian explanation of learning, now that species development, immune system function and the development of science itself can be accounted for in those terms. In effect, what is being proposed is the reinstatement of brain functioning as a biological process, with all that that entails for a modern biology of learning: essentially, that is a view of brains as Darwin machines (Plotkin, 1994), which generate and test ideas on their value. For science education researchers familiar with the modern history of ideas about generative learning (from Wittrock, 1974 onwards) and their precursors in the writings of Dewey (see, for example, Hickman, 1990) and Bronowski (1973/1992), this seems a small step to take, and it is one which is now well-supported by neuroscientific evidence (see, for example, Changeux, 1985; Edelman, 1992, 1993). However, its educational implications are powerful: no longer can learning be considered to occur by means of instruction, but rather by means of selection.

We now set out this biological basis for learning, focusing on its three central characteristics.

2. A biological basis for learning: An overview and three central characteristics

To argue a biological basis for learning is to argue that knowledge and knowledge-gaining (or learning) are evolved adaptations, examples of

> the apparent fit, the matching, of living things to the features and conditions of their world - be it the streamlined body shape of animals that move rapidly through water, the camouflaging coloration by which animals merge into their surroundings, or the cutting and slashing teeth of carnivores - ..... The matching is a result of living creatures somehow incorporating into themselves those aspects of the world that are matched. (Plotkin, 1994, p. xiii)

That is, "to know something is to incorporate the thing known into ourselves. Not literally, of course, but the knower is changed by the knowledge, and that change represents, even if very indirectly, the thing known" (Plotkin, 1994, p. ix). Edelman (1993) has put the point more particularly: "to survive in its econiche, an organism must either inherit or create criteria that enable it to partition the world into perceptual categories according to its adaptive needs" (p. 115). So, to adapt, to learn, individuals need to acquire effective ways to test or categorise the information they gain from their environment.

According to Plotkin (1994), individuals procure such knowledge in a nested hierarchy of ways: through their genetic code, by their own actions and from the culture. That is, such a view identifies, as learning, the development of genetic knowledge, within-organ knowledge (in brains and immune systems) and cultural knowledge (such as that of science), three processes which have previously appeared unrelated. Each of these ways of learning operates on a distinctive time scale. Thus, Edelman's and Plotkin's theory of mind satisfies Minsky's (1985) requirement that,

> Good theories of the mind must span at least three different scales of time: slow, for the billion years in which our brains have evolved; fast, for the fleeting weeks and months of infancy and childhood; and in between, the centuries of growth of our ideas through history. (p. 18)

The process of learning is a heuristic, as it "leads to discovery and invention" (Plotkin, 1994, p. 250). Invariant over all three scales of time, this heuristic consists of three actions: first, generating variants, secondly, testing them and thirdly, regenerating and hence propagating those variants that have survived the tests, that is, those that have been selected. Plotkin (1994) has termed this the g-t-r heuristic.

Animals have evolved this nested hierarchy of ways to learn in order to hedge their chances of survival. Their primary heuristic furnishes them with knowledge of their environment, which, by selection, becomes built into their genes and developmental pathways. However, this learning is slow, governed by reproductive frequency. Whilst organisms evolve slowly, organs like the brain and the immune system can adapt, within genetically constrained limits, to more rapid environmental change. However, whilst the brain, say, of one individual can generate, test and regenerate ideas effectively enough to track faster frequencies of environmental change than is possible by means of the primary heuristic alone, this secondary heuristic operates too slowly to enable that individual to track the fastest frequencies of environmental change. Hence, the evolution of a tertiary heuristic (consisting of the g-t-r mechanisms of culture), giving individual learners the benefit of knowledge that has been developed by cultures.

On this view, there are three characteristics which are central to learning. First, it is driven by values. Secondly, it is a process of generating and testing. Thirdly, it is developmental or progressive. We will now articulate each of these characteristics in turn so as to illuminate further this biological basis for learning

and prepare the ground for exploring its worth in advancing our understanding of generative learning in science.

Learning is driven by values

In Edelman's (1992) view, learning is "the means by which categorization occurs on a background of value to result in adaptive changes in behaviour that satisfy value" (p. 118). That there is a "background of value" against which learning occurs suggests that value influences what individuals select as the focus of their attention. That "adaptive changes in behaviour satisfy value" indicates that value filters the variants that are likely to survive the tests (or categorizations), and hence it constrains, retrospectively, the kinds of tests an individual selects.

Within this description lies a neuroscientific view of the mechanisms by which valuing controls learning. According to Edelman (cited in Millson & Sington, 1994), the processes of selection that give rise to categorization (and therefore, learning) are driven by specific neurons (or value systems) which exist deep down in the brain stem. These value systems have evolved to fire "when something is salient, when something might have [adaptive] value" (Edelman quoted in Millson & Sington, 1994, p. 10), for an individual. When a group of neurons, firing in the course of an individual's activity, triggers the firing of the value system, that particular neuronal group is strengthened or selected, making it more likely to fire again. So, according to Edelman, "[evolutionarily set] value gets imposed in the brain by the brain" (Edelman quoted in Millson & Sington, p.10); and "categorisation manifests itself in behaviour that appropriately fulfils the evolutionarily selected requirements of such life-supporting physiological systems" (Edelman, 1992, pp. 90-1). So, the brain is a Darwin machine, a "somatic selective system" (Edelman, 1992, p. 75) whose function is the adaptive matching of an individual's behaviour with its (ever-changing) environment, on the basis of an evolved and still evolving set of values. Hence, Edelman's insistence that neurobiology is a "science of recognition" (Edelman, 1992, p. 81), recognition of value.

Although his major emphasis is on primary values, it is also possible to distinguish secondary and tertiary values in Edelman's (1992) account.

Explicit in Edelman's (1992, 1993) use of the term value is survival or *primary* value, the controlling structures for which, whilst they are linked with the cortical system, evolved deep within the limbic brain. So, on Edelman's account, values are set through an individual's and a species' genetic history, so that an individual's present activity can be constrained in the interests of that individual's survival. This view of valuing is consistent with Plotkin's (1994) account of humans' having evolved a nested hierarchy of g-t-r heuristics: therein, the secondary and tertiary heuristics (those of the brain and the immune system, and the culture, respectively) evolved because of the adaptive (survival) value of gaining more up-to-date knowledge of changing environments than is possible on the basis of knowledge obtained through the very slowly changing gene pool (the primary heuristic) alone.

So, as a direct consequence of considering learning itself to be adapting, both Edelman (1992) and Plotkin (1994) have identified value first with survival value. Values develop iteratively and slowly: what has worked in the past projects an evolved and slowly evolving constraint upon the future. Thus, the primary heuristic "prime[s] and direct[s] the activities of the secondary heuristic" resulting in a "constrained intelligence" (Plotkin, 1994, p. 162).

However, humans' development of a secondary heuristic (in particular, the emergence of language and higher-order consciousness) admits three possibilities: that individuals can add to, modify or even deny their values. Edelman (1992) and Plotkin (1994) share the opinion that humans are able to modify their biological values only slightly. However, humans' brains can and do add to biological values to form their own "general goals, purposes and values" (Edelman, 1992, p. 161); or, "to generate [their] own causes for [their] behaviour" (Plotkin, 1994, p. 175). Here, such values, formed by individuals, are termed *secondary* values. The emergence of cultures is testimony to humans' "insertion of aims and purposes and ethical values into social systems" (Edelman, 1992, p. 163), which, "however far they are from biological value systems, almost certainly results from the original need for value in guiding the selectional systems of the brain" (Edelman, 1992, p. 163).

Sometimes, such cultural or *tertiary* values, developed so as to enhance the likely survival of cultures, appear to conflict with biological values, a situation Edelman (1992) described as the "tension ... [between] public and private good" (p. 163). At other times, the value systems of a culture usefully augment individuals' ways of learning, by providing access to cultural knowledge that has accumulated over many generations. For example, science provides access to tests which are acknowledged to have been extremely successful in limiting uncertainty (Plotkin, 1994). Of course, individuals must then subject such cultural knowledge to their own primary and secondary selectional systems if it is to become a part of those individuals' knowledge.

Learning as generating and testing

Not only does learning occur against a background of value, but value also filters the kinds of learning that are possible. In other words, evolutionary epistemology posits that learning is well-explained, as are all processes of adaptation, in terms of selection: first, variants are generated, next they are tested (or filtered on value) and then those selected by the test are propagated. This generate-test-regenerate heuristic (Plotkin, 1994) generically expresses a method for recognising value and adapting accordingly (whether this value is being recognised at the primary level of the genes, at the secondary level of the immune system and the brain, or at the tertiary level of the culture).

In the previous section, the values driving learning were recognised as having been built into living things over evolutionary time in the interests of enhancing these individuals' chances of survival. Now a stronger argument is being advanced: that a selectionist (g-t-r) heuristic has also evolved, over time, within the brains of living things. This means that the brains of living things have evolved a capacity to generate those variants from which selections, by value, can be made. Such a capacity to generate variants is clearly necessary for a selectionist view of learning: there needs to be something from which to select.

At its strongest, the implications of this argument are starkly nativist. According to Gazzaniga (1992),

> For the selectionist, the absolute truth is that all we do in life is discover what is already built into our brains. While the environment may shape the way in which any given organism develops, it shapes it only as far as preexisting capacities in that organism allow. Thus, the environment *selects* (emphasis in original) from the built-in options; it does not modify them. (pp. 2-3)

Within the brain, according to Edelman (1993), there are three principal and interactive processes of selection through which individuals learn: developmental selection, experiential selection and re-entry. He has described the first two as follows,

> The first occurs largely in embryonic and postnatal development, during which adjacent neurons tend to be strongly interconnected in collectives of variable size and structure called neuronal groups. The second process consists of alterations in synaptic strengths during an animal's activity, selecting the correlated responses of those neuronal groups that yield adaptive behaviour. (p. 115).

The third process of selection, re-entry, makes recursive links which serve to correlate and coordinate the maps of neural activity established through the first two processes.

On this account, brain development (the establishment of millions of branching connections between neurons) follows a unique path for each individual, within limits set down by the genes. Of the billions of interconnections that are possible during development, particular ones are selected, establishing a "primary repertoire" (Edelman, 1993, p. 117) of neuronal groups or circuits. Once an individual's primary repertoire has been formed, particular patterns of functioning neuronal groups are favoured over others (or selected) during the course of that individual's experience. These selections are made according to the value of particular behaviours, and they result in a strengthening of the synaptic connections which constitute that behaviour. Edelman (1993) has termed the set of such behaviours (with statistically increased likelihoods of occurring) an individual's "secondary repertoire" (p. 117). For these patterns of favoured neuronal groups to result in adaptive behaviour given the recurrence of similar environmental circumstances, they must be linked with each other, and with sensory receptor sheets, in space and time. This is accomplished through a third (higher order) selectional process whereby large numbers of ongoing, distributed and parallel two-way, recursive links within and between neuronal groups are established. In this way, several different patterns of neuronal group activity related to the same perceptual stimulus, for example, can be linked, new behaviours can be constructed and valued ones reconstructed.

This neuroscientific account of learning, at the level of neuronal group activity, depicts environments as exerting selection pressures on the behaviour of individuals. Learning is then a matter of categorising: of the many possible behavioural variants, those that match value requirements are selected, resulting in the (re)generation of adaptive behaviours. This process is well summarised by Plotkin's (1994) g-t-r heuristic.

Such a view of learning elegantly explains adaptive behaviours characteristic of species within populations of unique individuals. As well, it explains how individuals develop these adaptive behaviours as a result of the evolution of their species and their unique experience in environments that are changing rapidly and unpredictably. Individual variation and opportunistic circumstances are prized in that they provide a rich field from which to select; and rigour, of varying kinds and degrees, is introduced by way of the selection step. What is more, this explanation is achieved without having to reduce learning environments to chunks for instruction or posit an endless regress of homunculi to carry out information-processing tasks inside individuals' heads (Edelman, 1992).

This view of brain-learning in general also provides a sound foundation for understanding human intelligence; and it has the advantage, as Plotkin (1994) noted, of freeing human intelligence from being entirely reducible to matters of genetic determinism and past individual-environment interaction. According to Edelman (1992), human intelligence evolved as a result of interaction between linguistic capability and primary consciousness (the awareness or "correlated scene" (Edelman, 1992, p. 149) that exists for individuals by virtue of experiential selection and re-entry). Edelman (1992) described the significance of this interaction in these words,

> It is obvious why the acquisition of true speech leads to an enormous increase in conceptual power. The addition of a special symbolic memory connected to preexisting conceptual centers results in the ability to elaborate, refine, connect, create, and remember great numbers of new concepts. It is not the case that the language centers "contain" concepts or that concepts "arise" from speech. Meaning arises from the interaction of value-category memory with the *combined* (emphasis in original) activity of conceptual areas and speech areas. And although vocal speech was probably necessary for the evolutionary selection of the necessary morphological changes in the brain, after their emergence any gestural system in a speech community (such as sign language) could be employed if necessary. (p. 130)

As a result of this interaction, Edelman (1992) noted,

> As a syntax begins to be built and a sufficiently large lexicon is learned, the conceptual centers of the brain treat symbols and their references and the imagery they evoke as an "independent" world to be further categorized. A conceptual explosion and ontological revolution - a world, not just an environment - are made possible by the interaction between conceptual and language centers. (p. 150)

Being able to act on this "independent" world released humans from being tied to their present. As well, it enabled rich social communication. Together, Edelman (1992) noted,

> [these] allow for the anticipation of future states and for planned behaviour. With that ability come the abilities to model the world, to make explicit comparisons and to weigh outcomes; through such comparisons comes the possibility of reorganising plans. (pp. 133 and 135)

So, given a selectionist account of brain-learning "involving the unpredictable generation of variants," an intelligent individual "is able to generate the causes of its own behaviour" (Plotkin, 1994, p. 176); and "once intelligence has evolved in a species, then thereafter brains have a causal force equal to that of genes" (Plotkin, 1994, p. 177). However, the brain's causal force is profoundly biological, too. As Stein (quoted in Lewin, 1994) argued,

> The fact that we have bodies matters. It both constrains and enables the way we interpret the world. The way the brain evolved and human cognition developed was predicated on our interaction as individuals with the world. (p. 28).

In other words, according to this view, learning (including intelligent learning) is "situated" in the world and "embodied" (Brooks, 1991, p. 1227); and these characteristics permeate not only language (Lakoff, 1987; Lakoff & Johnson, 1980), but all aspects of how humans make meaning, including concepts (Edelman, 1992; Johnson, 1987; Lakoff, 1987) and memory (Edelman, 1992). Instead of being static repositories for an individual's meanings, memory and concepts are considered to be dynamic and procedural: memory is the process of categorising over again, given similar circumstances, and a concept is a capability of the brain to "[categorise] its own activities" (Edelman, 1992, p. 111),[1] a capability, Edelman (1992) contended, that evolutionarily preceded speech and does not require it. Nevertheless, as Edelman (1992) acknowledged, the emergence of language in a speech community has led human learning to flower, in that

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[1] White and Tisher (1986) noted,

> the observation by Sutton (1980) and White (1979b) that the language in which cognitive structure is discussed encourages the development of a static model, whereas memory may better be thought of as a dynamic property of the mind. No one has yet applied a dynamic model of cognitive structure in studies of science learning, and it remains a distant but potentially important prospect. (p. 884)

Edelman's (1992) theory satisfies White and Tisher's (1986) call for such a model. Furthermore, in 1993, when the findings of an empirical study (related to this conceptual exploration) were presented in a conference paper (Schaverien & Cosgrove, 1993), R. White (personal communication, July 11, 1993) noted that study's embodiment of a dynamic model of children's knowledge.

> An inner life ... becomes possible. This is tied to perceptual and conceptual structures, but it is highly individual (indeed, it is personal) and it is also strongly tied to affect and reward. It is higher-order consciousness, capable of modeling the past, present, future, a self, and a world. (p. 133)

Furthermore, highly individual creativity is well-explained here as a

> contribution ... to knowledge, by factors internal to the knower and hence unique to that individual intelligence. Such creativity cannot occur if [environmental] change is slavishly tracked by instructionalist devices. (Plotkin, 1994, p. 172)

So, according to neuroscience and evolutionary epistemology, learning, including intelligent learning, can be understood, in this fundamentally biological sense, to be a behaviour of selection on value: a behaviour of generating, testing and regenerating. However, as Minsky (1985) pointed out, to do better than mindless chance is difficult "without some notion of progress toward a goal," that is, without a "connection between [one's] generator and [one's] test" (p. 73). At the most fundamental level of adaptation, the notion of (survival) value satisfies Minsky's demand for a connection between generator and test. However, in an evolutionary context, the notion of development towards a goal is problematic. This third characteristic of learning, its developmental aspect, will now be clarified.

The developmental nature of learning

To argue that learning is at once an adaptation and developmental (or progressive) seems at first glance paradoxical. After all, adaptations result from chance variations acted on by the selection pressures of environments; and survival at any given time simply means falling within the constraints set by that environment. By its nature, however, development (or progression) is relative to a goal. So, it is necessary to explain in what sense a chance variation or adaptation could be considered to be goal-oriented or developmental.

This matter has been resolved by Edelman (1992) in two parts. First, it is possible to reject a teleological view (that is, one in which there are ultimate goals) and still retain a teleonomic view (Mayr, 1982), meaning a belief in the "prediction of the past" (Mayr, cited by Edelman, 1992, p. 161). Secondly, "evolution *can* (emphasis in original) select animals in such a way that *they* (emphasis added) have general goals, purposes, and values" (Edelman, 1992, p. 161). Putting these two part-resolutions together, Edelman (1992) wrote,

> The past experience of natural selection adjusts the set points of value systems (for example, those related to hunger, thirst, sexual responses) that are adaptive for survival. In our case, the brain of a conscious human being, serving as a somatic selective system, uses value constraints to project the future in terms of categories and goals. (p. 161)

This suggests an individualistic view of development occurring within a system of checks and balances where brains temper genetic determinism, and genes influence brains' intents; this is not to mention the reciprocal relations that exist between these two (genes and brains) and cultures. It suggests taking an epigenetic view of development. In Edelman's (1992) words, that is to say that "key events occur only if certain previous events have taken place" (p. 23); in Plotkin's (1994), it is to recognise that

> each individual is, in a real sense, created anew, the unique outcome of an immensely complex series of interactions between the different parts of that individual; and also between its genes, its developing parts and its environment. Epigenesis is the word used to describe this complicated, integrated, dynamic and probabilistic process of development. (p. 122)

Neuroscientific research already suggests that brain growth and development are epigenetic (Changeux, 1985; Edelman, 1992, 1993). Such significant structural and functional variability exists in individual nervous systems that "although there is an obvious commonality of neural structure within a species, the degree of individual variation far exceeds that which could be tolerated for reliable performance in any machine constructed according to current engineering principles" (Edelman, 1993, p. 115). So, whilst brain development is obviously a matter of genetics, it is not reducible to genetics alone; "Genes control the whole business indirectly ... but the actual microscopic fate of a cell is determined by epigenetic events that depend on developmental histories unique to each individual cell in the embryo" (Edelman, 1992, p. 62).

On this view, development results from a subtle, variable and unpredictable mix of individual and environmental circumstances. Such a perspective on development requires taking a projective view of learning, considering it to be a prediction of a unique individual's past, within genetically evolved constraints, rather than a pre-ordained, invariant sequence of developmental stages. On this individualistic view of learning, as key events occur, a choice of futures comes into view.

This view of development, as epigenesis, acknowledges the selection pressures exerted by environments on unique and active individuals. However, it does not attribute single or ultimate causes. Instead, at each point in an individual's development, a complex, dynamic and idiosyncratic system of factors, constrained by genes and environment, results in a particular unique set of possible futures; and the goals and values that individuals themselves generate play a critical part in the series of selections that will map these individuals' development over time.

In summary, this, then, is a profoundly biological view of learning which casts it as an adaptive behaviour of living things. As such, it is recognised to occur at the three nested levels of genes, within organs (such as brains and immune systems) and within cultures. At each of these three levels, learning occurs, on this view, by means of the heuristic of generating variants, testing those variants on their value and regenerating those that survive the test. A particular and significant example of such learning, one which has evolved to a high level of sophistication in our species, is brain-learning. Here, brain-learning is that adaptive behaviour of progressively, individualistically and intelligently generating, testing and regenerating ideas, on values honed over our species' evolutionary history as well as during individuals' own lifetimes.

Not only does such a view of learning appear to be in tune with generative learning in science, but it appears to advance our understanding of it significantly. It is to the fit between this biological view of learning and generative learning in science that we now turn.

3. Towards a biological basis for generative learning in science

This account provides us with new ways to think about generative learning in science, by advancing our understanding of the learning (and teaching) of science as well as of scientific knowledge itself. All three of the characteristics (valuing, generating and testing and epigenetic development or progression) identified as being central to and well-explained by a biological view of learning feature prominently in writings about generative learning in science. Here, we consider the significance of this overlap and, in so doing, we initiate the detailed discussion which is now necessary if we are to explore the worth for education of this biological view of learning.

Generativity is well-recognised in science education research and in science learning; and so, naturally, is testing. As has already been noted, generating and testing so often occur so close together in scientists' thinking as to be inseparable by consciousness (Medawar, 1967/1982). In generating and testing cycles of their own, science educators have researched ideas that children generate about phenomena and designed (and tested) ways of encouraging children to evaluate these ideas (for example, Erickson (1979) described children's views of heat and temperature; Osborne & Cosgrove (1983) identified several theories about the changes of state of water). It was Wittrock (1974) who articulated a view of the mind as generator, a view which was later incorporated into a teaching model for generative learning (Cosgrove, Osborne & Tasker, 1982; Cosgrove & Osborne, 1985), a generative learning theory (Osborne & Wittrock, 1983, 1985), and a generative science teaching approach (Wittrock, 1994). In his behaviour-based account of the development of mind, Minsky (1985) identified a generate and test method of problem-solving with trial and error; and Papert's (1991) constructionist approach to learning recognised and tapped the centrality of generating and testing.

Encouraging learners to generate their own transitional frameworks and analogies has recently proved effective in helping them towards a deep understanding of aspects of electric current (Cosgrove, 1995). Such an approach upholds the importance of learners' own generating and testing in the epigenetic development of their understanding. It contrasts sharply with the discontinuity often assumed to exist between novices' and experts' knowledge (Larkin, 1983; McCloskey, 1983). Once learners' views are no longer considered to be a learning barrier, careful analysis can uncover aspects of their knowledge that are continuous with and may be used by them to generate scientific understandings (diSessa, 1990; Smith, diSessa & Roschelle, 1993).

However, even though generating and testing are widely acknowledged as central to learning, educators have generally not recognised that a belief in learning as generating and testing suggests that learning occurs principally by *selection*, not instruction; and this despite the appearance of neo-Darwinian ideas, as already noted, in many fields of human thinking. Of course, a strongly held belief in Piaget's stage developmental theory of learning has impeded consideration of the possibility that learning is epigenetic. According to Changeux (1985), considering the comparative subtlety of selectionist explanations, it is not surprising that historically instructionist explanations have preceded them,

> An instructive concept consists of only one step. It is the simplest possible approach. Moreover, whether we like it or not, it contains an "egocentric" component. "Nature directs forms" much as the sculptor models clay into a statue. The image of human behavior that first occurs to the scientist's brain is transposed into elementary mechanisms that have nothing to do with it and are situated at a completely different level of organization. The concept of selection, on the other hand, implies further reflection. It involves two steps, and it satisfies the quest for a material mechanism totally

> devoid of "intentional" aspects. It is natural that this more complicated procedure, more difficult to execute, should have systematically appeared in second place throughout the history of scientific thought. (p. 281)

Whatever the reasons for this slowness to appreciate the selectionist (rather than instructionist) basis of learning, we, like others in diverse research fields (for example, Pinker, 1994; Sacks, 1995; Thelen and Smith, 1994), are beginning to recognise the fruitfulness of such a view in explaining our empirical findings. Young children's scientific and technological ingenuity and their profound philosophical inquiries are well-explained in selectionist terms (Cosgrove and Schaverien, 1996). So, too, is the re-valuing required for experienced primary school teachers to learn to teach science generatively (Schaverien and Cosgrove, 1994; Schaverien and Cosgrove, under review).

As well, this modern biology of knowledge provokes urgent consideration of a particular epistemology for generative learning in science. It suggests that such an epistemology might usefully be based on recognising evolved and evolving values as a basis for scientific knowledge, on acknowledging that it is by valuing that humans act in the present in anticipation of the future. As Bronowski (1973/1992) argued,

> Knowledge is not a loose-leaf notebook of facts. Above all, it is a responsibility for the integrity of what we are, primarily of what we are as ethical creatures. ... every civilization has gone forward because of its engagement with what it has set itself to do. (pp. 267, 269)

In addition to such conceptual implications of this biological view of learning, there are also significant strategic implications for science teaching (Schaverien and Cosgrove, in preparation) and for teacher education in science (Schaverien and Cosgrove, under review) which we and others (Aubusson, 1996; Clark, 1996) are already exploring and developing.

In our opinion, patient exploration, in these and other ways, of the fruitfulness of this biological view is now paramount, for, as we noted at the start of this paper, educational research could profit greatly from a powerful and coherent explanatory theory, such as those that have characterised the modern history of biology. Somewhat paradoxically, it is Bohm and Peat's (1987) view that science itself has often overemphasised testing of ideas at the expense of generating them,

> a new idea which has broad implications may require a long period of gestation before falsifiable inferences can be drawn from it. For example, the atomic hypothesis, first suggested by Democritus twenty-five hundred years ago, had no definitely falsifiable inferences for at least two thousand years. New theories are like growing plants that need to be nurtured and cultured for a time before they are exposed to the risks of the elements. ... Clearly, it makes little sense to go to all the effort of attempting to falsify a hypothesis when it has never actually been confirmed, or if it has little plausibility.
>
> Fundamental ideas need to be sheltered for a while in a spirit of free creative "play". (p. 59)

It is our intent, in writing this paper, to initiate a period of gestation for this fundamental idea.

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